# SUZAKU OBSERVATIONS OF THE ULTRACOMPACT BINARY SYSTEM 4U 1626–67

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## ABSTRACT

The accretion–powered pulsar 4U 1626-67 experienced a new torque reversal at the beginning of 2008, after about 18 years of steadily spinning down. We present a spectral analysis of this source using two pointed observations performed by Suzaku in 2006 March and in 2010 September. We confirm with Suzaku the presence of a strong emission-line complex centered on 1 keV, with the strongest line being the hydrogen-like Ne Ly$\alpha$ at 1.025(1.5) keV. We were able to resolve this complex with up to eight emission lines. A dramatic increase of the equivalent width of the Ne Ly$\alpha$ 1.021 keV after the 2008 torque reversal occurred, reaching almost the same value measured by ASCA in 1993. In addition, we confirm the general decrease trend of the equivalent widths during the spin-down period. We also report on the detection of a cyclotron line feature centered at $\sim$37 keV. In spite of the fact that a dramatic increase of the X–ray luminosity (0.5–100 keV) of a factor of $\sim$3.5 occurred between these two observations, no significant change in the energy of the cyclotron line feature was observed. However, the intensity of the $\sim$1 keV line complex increased by an overall factor of $\sim$10.

*Subject headings:* accretion, accretion disks — binaries: — pulsars: individual (4U 1626–67 ) — stars: neutron — X–rays: stars

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## 1. INTRODUCTION

4U 1626–67 is a Roche-lobe filling binary system, where matter from the companion flows from the L1 point into an accretion disk (Reynolds et al. 1997). This low mass X–ray binary (LMXB) consists of a 7.66 s X–ray pulsar accreting from an extremely low mass companion (0.04 M$\odot$ for $i = 18^o$)(Levine et al. 1988). Although orbital motion has never been detected in the X–ray data, pulsed optical emission reprocessed on the surface of the secondary revealed (Middleditch et al. 1981) the 42 min orbital period, confirmed by Chakrabarty (1998). Most likely the binary system contains a hydrogen–depleted secondary to reach such a short orbital period (Paczynski and Sienkiewicz 1981). The faint optical counterpart (KZ TrA, $V\sim$17.5) has a strong UV excess and high optical pulse fraction (McClintock et al. 1977, 1980).

4U 1626–67 has reversed the sign of the torque in only two occasions since its discovery by *Uhuru* (Giacconi et al. 1972). Monitoring of the source by the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (*CGRO*) starting in April 1991, found the pulsar spinning down, implying a changed sign in the accretion torque (Wilson et al. 1993; Bildsten et al. 1994). It was estimated that the reversal occurred in mid-1990. More recently, our daily monitoring of 4U 1626–67 with *Fermi*/GBM starting in 2008 August, found the pulsar again spinning–up rather than spinning–down. *Swift*/BAT observations allowed us to cover the evolution of this second torque reversal. The transition took place at around MJD 54500 (2008 Feb 04) and lasted approximately 150 days (Camero-Arranz et al. 2010).

A 48 mHz quasi-periodic oscillation (QPO) has been detected in the X–ray emission (Shinoda et al. 1990; Kommers et al. 1998). Orlandini et al. (1998) inferred a neutron star magnetic field in the range of (2.4–6.3)$\times 10^{12}$ G. To compute this magnetic field range a source distance of 5–13 kpc was assumed (Chakrabarty 1998, and references therein). A $\sim$37 keV absorption cyclotron feature was found in the 0.1–200 keV *BeppoSAX* spectrum (Orlandini et al. 1998). The X–ray broad-band continuum was fitted with low–energy absorption, a blackbody, a power law and a high energy cutoff.

Angelini et al. (1995) using the ASCA observatory discovered for the first time a strong emission-line complex centered on 1 keV in the X–ray spectrum of 4U 1626-67. The strongest line was identified as hydrogen-like Ne Ly$\alpha$ at 1.008 keV. The strength of the neon emission compared to the expected iron L complex implied a large neon overabundance.

We present a spectral analysis of 4U 1626–67 with Suzaku, using two observations from 2006 March and 2010 September. This allows us to better characterize the recent torque reversal occurred in 2008 February.

## 2. OBSERVATIONS and ANALYSIS

The instruments on Suzaku (Mitsuda et al. 2007) are the X-ray Imaging Spectrometer (XIS; Koyama et al. (2007)) CCD detector covering the 0.3–10 keV band, and the Hard X-ray Detector (HXD; Takahashi et al. (2007)) comprised of the PIN diode detector (PIN) covering the 10–70 keV band and the gadolinium silicate crystal detector (GSO) covering the 60–600 keV band. The XIS has four separate detectors, XIS 0–3, with XIS 1 being a backside illuminated CCD and the others frontside. XIS 2 was lost due to a micrometeor hit in late 2006.

The first Suzaku 4U 1626–67 observation occurred in 2006 March (MJD 53797), and thus before the torque reversal in 2008. During this observation the spacecraft aimpoint was optimized for the XIS detectors, and Suzaku was run in a 1/8 window mode with 1 s integration time, and an effective area of $128 \times 1024$ pixels. The second observation in 2010 September (MJD 55444) was also placed on XIS aimpoint but run in a 1/4 window mode, with 2 s integration time and an effective area of $256 \times 1024$ pixels. For this observation only 3 XIS detectors were available, as we discussed in the previous paragraph. The Suzaku data were reduced with tools from the HEASOFT v6.11 package (Arnaud 1996) and CALDB release 20110804. Following the Suzaku ABC guide[1], the first step of our analysis was to reprocess the data by running the FTOOL *aepipeline* for the XIS, the PIN and the GSO. The pipeline performs calibration as well as data screening.

The attitude of the Suzaku spacecraft exhibits variability over the course of the observations and therefore the image of the source is not at a fixed position on the CCD. This is due to a thermal distorsion of the optical bench. As described in Nowak et al. (2011), standard processing reduces this variability and improves the PSF image. However, this processing is not enough and thus we used the aeattcor2.sl software. Unfortunately, we could not correct fully the double image of the source in the XIS images for the second observation. We used the ftool *pileest.sl* to estimate the amount of pileup in the XIS images and disregarded regions with >8% pileup fraction during the spectral extraction. For the first observation the pileup fraction remained below this limit in the entire source extraction region (a circle of $\sim 70''$ radius centered on the source image). In the second observation pileup fractions of up to 15% were reached in the center of the source image so the extraction region consisted of a circle of $\sim 130''$ radius minus a central circular exclusion region with a $\sim 35''$ radius.

The primary tool for extracting data products (spectra, lightcurves) from XIS data is *xselect*, which is part of the general HEAsoft distribution. Events in the XIS detectors were

[1]http://heasarc.nasa.gov/docs/suzaku/analysis/abc

in the 3×3 and 5×5 editing modes. With *xselect* we applied to the cleaned events filters with the good times intervals. Source and background regions are created from the image. The filtered events were then used to create source and background spectra for the desired extraction regions. Products from the two editing modes were added. The XIS spectra were grouped close to the energy resolution of the detectors (see Nowak et al. (2011)). We created response matrices and effective area files with the *xisrmfgen* and *xissimarfgen* tools, respectively. The calibration of the XIS is uncertain around the Si K edge, thus events in the 1.8–2.0 keV range were excluded in the fitting.

For the PIN, we extracted spectra from the cleaned event files using *hxdpinxbpi*. This tool produces the dead time corrected PIN source spectrum as well as the PIN background spectrum. The non X–ray background is provided by the Suzaku team and can be downloaded from HEASARC (ftp://legacy.gsfc.nasa.gov, †) archive[2]. The PIN spectra were grouped to have a signal-to-noise ratio $\gtrsim 10$ in each energy bin, and we considered spectra between 14–100 keV. We point out that due to the changes in instrumental settings the PIN response matrices are different depending on the epoch of the observation.

The GSO spectra were created starting with the clean event files using the *hxdgsoxbpi* tool. The background was downloaded from HEASARC[3]. Response files were taken from the CALDB database and the GSO ARF file from the team[4]. The distributed GSO Non X–ray Background is grouped, so GSO spectra have to be grouped accordingly, using the spectral binning given by the file *gsobgd64bins.dat* available at HEASARC[5]. GSO spectra were restricted to the ∼60-100 keV range.

## 3. RESULTS

The 0.5–100 keV broad-band spectrum obtained using XIS (a combination of detectors 0 and 3), PIN and GSO was fitted in XSPEC 12.7.0. We used a canonical model which allowed us to compare our spectral study with previous works (Angelini et al. 1995; Pravdo et al. 1979; Orlandini et al. 1998; Krauss et al. 2007; Jain et al. 2010, among others) and update the long-term X–ray flux history of 4U 1626–67 relative to the flux measured by *HEAO 1* (Chakrabarty et al. 1997; Krauss et al. 2007; Camero-Arranz et al. 2010).

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[2]†/suzaku/data/background/pinnxb_ver2.0_tuned

[3]†/suzaku/data/background/gsonxb_ver2.0

[4]http://www.astro.isas.ac.jp/suzaku/analysis/hxd/gsoarf/

[5]†/docs/suzaku/analysis/gsobgd64bins.dat

The first model includes low-energy absorption, a blackbody component, a power law, a high-energy cutoff at $\sim$20 keV and a Gaussian absorption line at $\sim$37 keV (PHABS (GAUSS+BBODY+POWLAW) HIGHECUT*GABS)*CONST. The abundance was set to wilm (Wilms et al. 2000). A broad line near 6.4 keV improved the fit indicating the presence of an iron line. The addition of the 37 keV cyclotron line feature was also needed after an initial inspection of the residuals (see Fig 1). However, the $\chi^2$ was unacceptable using this model. The residuals still indicated a strong line feature at 1 keV. Following the study by Angelini et al. (1995), we added up to 7 narrow Gaussian lines, with their widths fixed to the ASCA values (10 eV for all but the 1.46 keV line with 57 eV), and the only requirement for inclusion was reducing the $\chi^2$. We also fit a recombination edge yielding a similar $\chi^2$ compared to that obtained using a broad Gaussian line. The edge (and temperature) obtained for the first and second observation are 1.45$\pm$0.05 keV ($42^{+50}_{-40}$ eV) and 1.47$\pm$0.03 keV ($45^{+34}_{-25}$ eV), respectively. A posteriori inspection of the residuals suggested the presence of an extra Gaussian component at energy $\sim$1.34 keV. Therefore, up to 8 Gaussian components were included in the final fit. The summary with the best fit spectral parameters obtained has been divided in two tables for clarity. Table 1 shows the best fit broad band spectral parameters and Table 2 summarizes the emission lines detected by Suzaku. As a check, we fit the broad-band spectrum using different combination of XIS detectors yielding similar results.

A drastic luminosity increase happened between the two observations, changing from $L_{(0.5-10\,keV)} \approx 2.5\times10^{34} d^2_{kpc}$ to $10\times10^{34} d^2_{kpc}$ erg s$^{-1}$. Surprisingly, the value of the center of energy of the cyclotron line feature does not exhibit a significant change. On the other hand, the $N_H$ column density dropped while the black body temperature increased by a factor of $\sim$2. The rest of the broad band parameters remained practically the same before and after the 2008 reversal.

Regarding the line emission at low energies, for the first observation only five of the eight fitted lines (seven initially observed by ASCA) were significantly detected. For the ones that we could not constraint, they were fixed to the ASCA values (accepting only lower flux intensity values). Absorbed fluxes for the first model in the 0.5–10 keV, 2–10 keV, 2–20 keV and 2-50 keV bands are 2.08(4), 1.78(2), 3.15(3), 4.81(3) $\times10^{-10}$ erg cm$^{-2}$s$^{-1}$ and 1.0(3), 0.706(9), 1.2(1), 1.37(9) $\times10^{-9}$ erg cm$^{-2}$s$^{-1}$, for the first and second Suzaku observations, respectively.

## 4. DISCUSSION

In 1990, the torque reversal experienced by 4U 1626–67 was accompanied by a spectral transition and a change in the luminosity (Yi and Vishniac 1999). The power law photon index changed from 1.6 (Pravdo et al. 1979; Angelini et al. 1995) to ∼0.6 (Owens et al. 1997). The black body temperature also decreased from ∼0.6 keV to ∼0.3 keV. Our Suzaku observations revealed that after the 2008 torque reversal 4U 1626–67 reached almost the same luminosity level as in 1977 (see Fig. 2), but within a period of only ∼2 years. Despite the fact that the black body temperature transitioned from ∼0.23 keV back to ∼0.6 keV in 2010, the photon index of ∼1 did not show any significant change. The temperature after the 2008 torque reversal is in agreement with the value obtained with *RXTE* (Camero-Arranz et al. 2010; Jain et al. 2010). For 4U 1626–67 a photon index of ∼1 has been observed by several missions during the spin–down period, e.g. *ASCA* (Angelini et al. 1995), *BeppoSAX* (Orlandini et al. 1998), *Chandra* and *XMM* (Krauss et al. 2007; Schulz et al. 2001). In Camero-Arranz et al. (2010, and references therein) we found that the spectral evolution of 4U 1626-67 during the 2008 torque reversal differed from that expected in models, which suggested significant changes of the accretion flow structure in spin-up/spin-down transitions. The spectrum became hardest during the reversal and the value of the hardness ratio before and after these events did not differ significantly. This indicated that the recent torque reversal could be associated with changes of physical conditions in the inner part of the disk or/and in the region of its interaction with the magnetosphere.

In the present work, following Angelini et al. (1995), we have decomposed the strong emission-line complex centered on 1 keV found in the Suzaku X–ray spectrum of 4U 1626-67. In both Suzaku observations the strongest line is the hydrogen-like Ne Ly$\alpha$ line at ∼1.025 keV, in agreement with the ASCA observations. The broad feature at ∼1.48 keV found by Angelini et al. (1995) was close to the expected energy of the H–like Ne recombination edge, H–like and He–like Mg emission at 1.36, 1.47 and 1.34 keV, respectively. The measured 57 eV broadening of the line at ∼1.48 keV also with Suzaku, suggests that we may be also detecting the recombination continuum of Ne. Furthermore, with Suzaku an eighth line centered at ∼1.34 keV was detected, which most likely is the He–like Mg line. We would like to point out that this line energy is so close to the Ne recombination continuum and the Mg K lines, and therefore we cannot exclude a different origin for the detected line.

During the spin–down period, comparing the strength of the first seven lines detected in the first Suzaku observation with previous measurements by *ASCA*, we see that the overall decrease is of the order of ∼2.5 (see Table 2). Before the 2008 torque reversal, X–ray missions like *BeppoSAX* (Owens et al. 1997), *Chandra* (Schulz et al. 2001; Krauss et al. 2007) and *XMM* (Krauss et al. 2007) were able to resolve only up to 3 or 4 lines of this complex. In

general, the measurements of the intensity of those lines are in agreement with our results. During the new spin–up period after the 2008 torque reversal, the flux of the lines increased by a factor of $\sim$5 except the Ne Ly$\alpha$ line at 1.021 keV that increased by a factor of 10. This result is expected taking into account such a change in luminosity. Unfortunately, during a previous spin-up period there was only one measurement of the $\sim$1 keV complex by the *Einstein* observatory in 1979, and it was not resolved due to the lower data quality. The overall luminosity decrease associated with the 1990 torque reversal was a factor of $\sim$3 in the 0.5–10 keV range (Angelini et al. 1995, and references therein). Krauss et al. (2007) found a decrease of the equivalent widths of the Ne He$\alpha$ 0.914 keV and Ne Ly$\alpha$ 1.021 keV lines during the spin-down period. The behavior of the EW for the O He$\alpha$ 0.568 keV and O Ly$\alpha$ 0.653 keV lines was more flat during the same period. With Suzaku we found a dramatic increase of the EW of the Ne Ly$\alpha$ 1.021 keV line after the 2008 torque reversal. The EW for this line reached almost the same value measured by ASCA in 1993. For the rest of the lines the increase is not that pronounced. We also confirm the general decrease trend of the equivalent widths during the spin-down period.

In 1993, the strength of the neon emission in the ASCA spectrum of 4U 1626–67 implied a large neon overabundance, suggesting that the companion star was burning (or had burned) helium. A more recent study by Schulz et al. (2001) with *Chandra* found that the emission lines had a double-peaked profile. They appear to originate in hot ($\approx 10^6$ K) dense material just below the X-ray–heated skin of the outer Keplerian accretion disk, or else possibly in a disk wind driven from the pulsar's magnetopause. Based on the inferred local abundance ratios, they claimed that the mass donor is probably the 0.02 M$\odot$ chemically fractionated core of a C-O-Ne or O-Ne-Mg white dwarf which has previously crystallized.

Spectroscopic observations of this iron K-fluorescence line are one of the most useful probes to investigate the matter distribution surrounding the X–ray binary system. Kii et al. (1986) concluded that the matter accumulated on the Alfvén shell seems to be the most likely site to reprocess the iron k-fluorescence line in disk-fed X-ray pulsars like 4U 1626–67, rather than the accretion disk and/or the atmosphere of the companion star. They obtained an upper limit of EW$\leq$60 eV for this line. With Suzaku we were able to find positive evidence for the iron emission line around 6.4 KeV. The iron K-fluorescence line from neutral or lowly ionized iron has been observed in 4U 1626–67 in the past by different observatories (Pravdo et al. 1979; Owens et al. 1997; Camero-Arranz et al. 2010; Jain et al. 2010). In the present observations we found that the EW changed from $\sim$70 eV to 24 eV, the opposite to the expected behavior (that is, no change). These two different values for the iron line EW might suggest that changes in the matter accumulated on the Alfvén shell occurred after the 2008 torque reversal.

Orlandini et al. (1998) discovered a 38.6(9) keV cyclotron resonance feature in the broad band spectrum obtained with *BeppoSAX* observations from 1996. The inferred magnetic field strength at the neutron star surface was $(3.2 \pm 0.1) \times 10^{12}(1+z)$ G, where z is the gravitational redshift. In addition, they assumed that the quasi-periodic oscillation frequency was due to the beating between the the pulse frequency and the Keplerian motion at the magnetospheric radius. Assuming a distance $5 \leq d_{kpc} \leq 13$, they obtained $2.4 \leq B_{12} \leq 6.3$. Our measurements of the energy of the cyclotron line feature with Suzaku $36.8^{+0.9}_{-0.8}$ and 37.7(7) are consistent within errors. They are in agreement with the *BeppoSAX* results, taking into account the uncertainties of the measurements. The fact that the value of the center of energy of the cyclotron line feature did not exhibit a notable change at different luminosity states, resembles the only case of the Be/X-ray binary system A 0535+26 (Caballero et al. 2009), but contrary to sources like Her X–1 or V 0332+53 (Pottschmidt et al. 2011, and references therein).

More recently, Zhang and Li (2010) proposed a new explanation for the 2008 torque reversal. They claimed that winds or outflows from the neutron star and the accretion disk may play an important role in accounting for the spin-down in the disk-fed neutron stars like 4U 1626-67. The essential idea is that the spin-down is induced by stellar and disk winds (outflows) that take away the angular momentum of the neutron star. Thus a significant decrease of the mass transfer rate and possible propeller effect are not required. The main limitation of this model is the mechanism originating these winds.

In general, torque switching models explain this behavior by the effect of the accretion flow, and the neutron star is assumed to be acting as a solid body. Observations of glitches (and glitch-like events in accreting pulsars) as well as unusually rapid spin-down phases suggest that the this may not be the case, and the contribution of torque accumulated in the interior of neutron stars may be significant.

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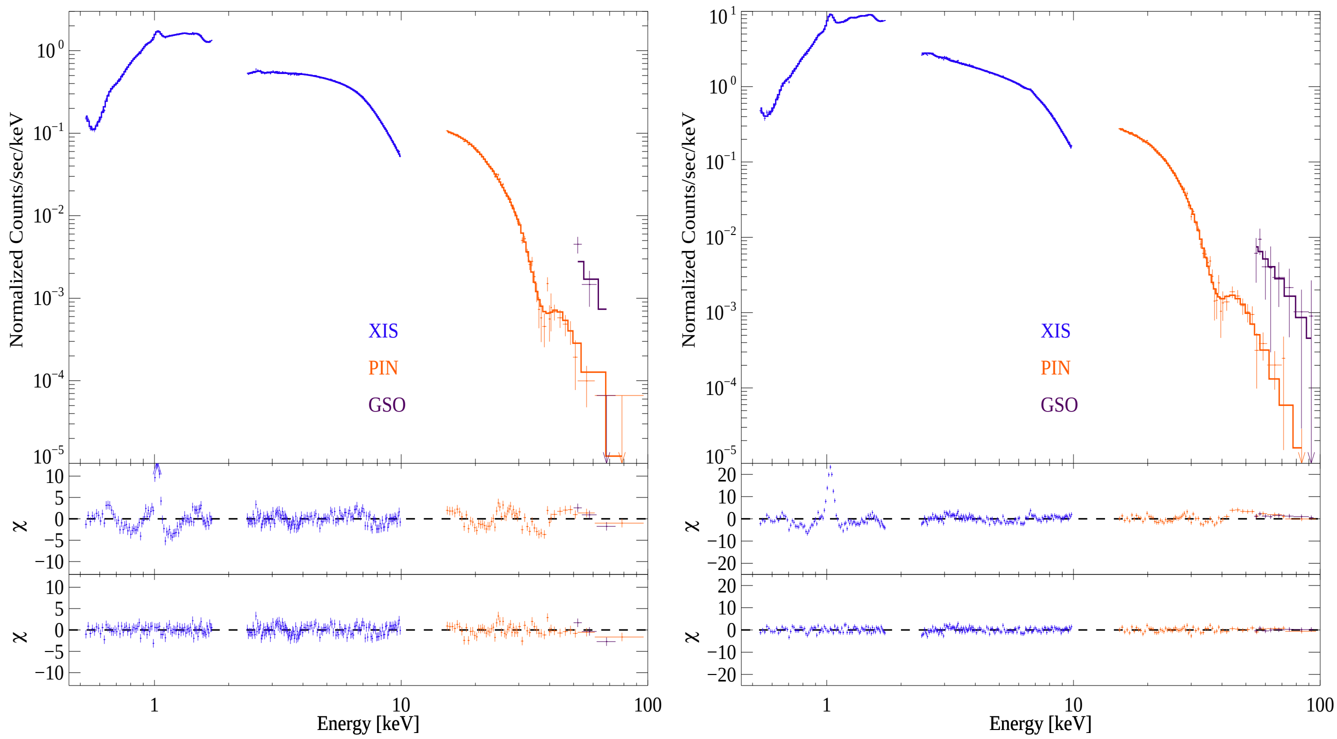


Fig. 1.— The main panels show the Suzaku broad-band spectrum before (left panel) and after (right panel) the 2008 torque reversal. Black points denote XIS data (0.5–10 keV), PIN data points are in red (14–100 keV) and GSO in purple (∼60–100 keV). The residuals after fitting a simple model are shown in the middle panel, with no line emission and cyclotron line feature included. The bottom panel shows the residuals after fitting the line complex at ∼1 keV, the ∼6.5 keV iron line and the ∼37 keV cyclotron line.

Table 1: BEST BROAD BAND FIT SPECTRAL PARAMETERS$^{mod}$

| Observation | $N_{\rm H}^k$ | $\alpha^*$ & norm | $E^\dagger_{cut}$ | $E^\dagger_{Fold}$ | $E^\dagger_{CRF}$ & $\sigma^\dagger_{CRF}$ | $T^\dagger_{BBody}$ & norm$^a$ | Flux$^b$ | constant factor$^{\dagger\dagger}$ | $\chi^2_r$(DOF) |
|---|---|---|---|---|---|---|---|---|---|
| 400015010 (MJD 53797) | 1.15(2) | 0.847(9) 0.0163(2) | 19.3(5) | 13(1) | $36.8^{+0.9}_{-0.8}$ 3.5(7) | $0.231^{+0.01}_{-0.009}$ 1.7(7) | 0.63(4) | 0.71(1) 0.5(3) | 1.4(296) |
| 405044010 (MJD 55444) | 0.2(1) | 0.90(3) 0.042(2) | 21.3(6) | 14(1) | 37.7(7) 4.2(6) | 0.520(8) 21.5(7) | 2.5(4) | 0.56(2) 04.(2) | 1.2(293) |

$^{mod}$(PHABS (8 GAUSSIANS+GAUSSIAN+ BLACKBODY +POW)*HIGHECUT *GABS)*CONST; $^k$ $\times$ $10^{21}$ cm$^{-2}$; $^*$ Photon Index with normalization units in photons keV$^{-1}$cm$^{-2}$s$^{-1}$ at 1 keV; $^\dagger$ keV; $^a$ $\times 10^{-4}$ (Lumin/$10^{39}$ erg s$^{-1}$)(d/10$kpc$)$^{-2}$; $^b$ $\times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ (0.5–100 keV); $^{\dagger\dagger}$ Intercalibration factors (PIN/ XIS03 and GSO/XIS 03) with XIS 03 being a spectrum combination from detectors XIS 0 and XIS 3

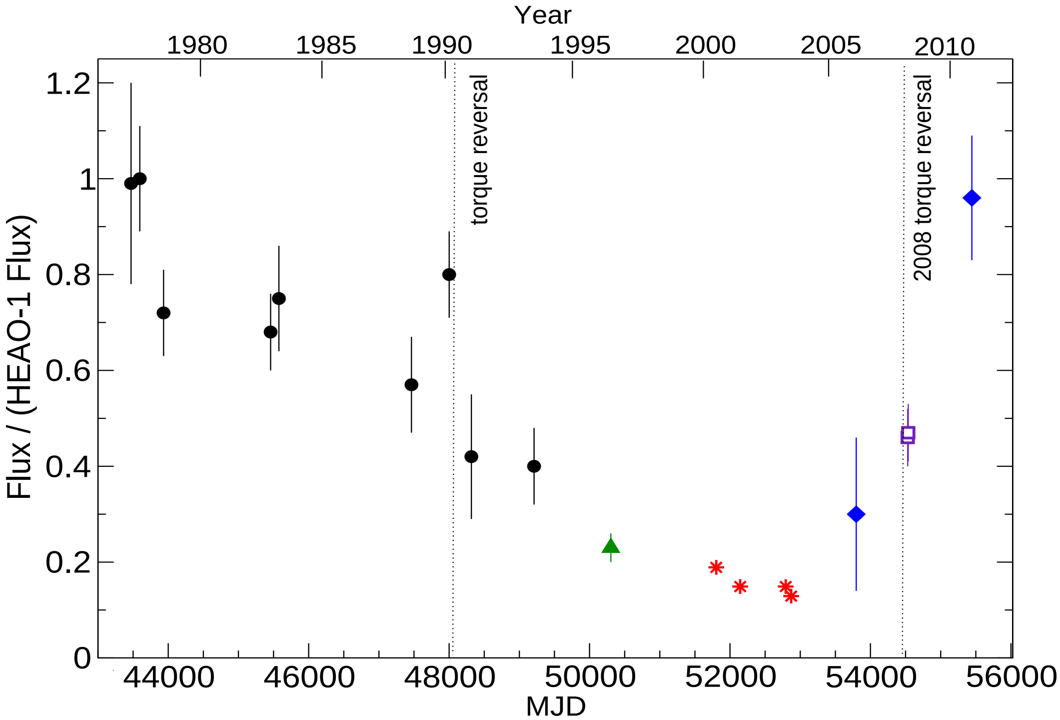


Fig. 2.— The X–ray flux history of 4U 1626–67 relative to the flux measured by *HEAO 1*, in the same energy band, from previous works (Chakrabarty et al. (1997): circles; Orlandini et al. (1998): triangle; Krauss et al. (2007): stars; Camero-Arranz et al. (2011) unfilled squares) and the two Suzaku observations (blue diamonds) in the 0.7–60 keV band.

Table 2: FIT RESULTS ON LINE EMISSION

| Observation | Expected (keV) | Line Energy 400015010 | (keV) 405044010 | Intensity* 400015010 | 405044010 | EW (eV) 400015010 | 405044010 |
|---|---|---|---|---|---|---|---|
| O He$\alpha$ | 0.568 | 0.568(fixed) | 0.57(3) | $4^{+3}_{-1}$ | $15.075^{+0.01}_{-0.009}$ | 7.3 | 13.2 |
| O Ly$\alpha$ | 0.653 | 0.659(7) | 0.661(7) | 3.2(9) | 16.609(3) | 13.5 | 15.6 |
| Ne He$\alpha$ | 0.914 | 0.928(7) | 0.929(4) | 1.4(3) | 8.3690(9) | 7.1 | 9.3 |
| Ne Ly$\alpha$ | 1.021 | 1.025(2) | 1.031(2) | 3.7(2) | 38.399(9) | 22.3 | 45.7 |
| Ne He$\beta$ | 1.084 | 1.084(fixed) | 1.11(3) | 0.2(fixed) | $2.3(^{+0.8}_{-0.7})$ | 1.2 | 2.9 |
| Ne Ly$\beta$ | 1.210 | 1.210(fixed) | 1.25(2) | 0.2(fixed) | 3(1) | 0.7 | 4.6 |
| He-like Mg$^{\dagger}$ | 1.34 | 1.33(3) | 1.36(1) | 0.4(1) | 3.2(8) | 2.6 | 4.8 |
| Ne Recombo | 1.362 | 1.48(2) | 1.51(2) | 0.9(2) | 4.3(8) | 8.3 | 14.9 |
| Fe K-fluor. line | 6.4 | 6.3(2) | 6.73(7) | $1.5^{+0.6}_{-0.5}$ | $1.77^{+0.07}_{-0.1}$ | 70 | 24 |

* photons $10^{-4}$cm$^{-2}$s$^{-1}$; $^{a}$ the widths of all the lines were fixed to the ASCA values (see text); for but the iron line the widths were not fixed (values obtained: 0.8(2) eV and 0.12(2) eV, respectively); $^{\dagger}$ the energy of this line is so close to the Ne recombination continuum and the Mg K lines, and therefore we cannot exclude a different origin for the detected line.